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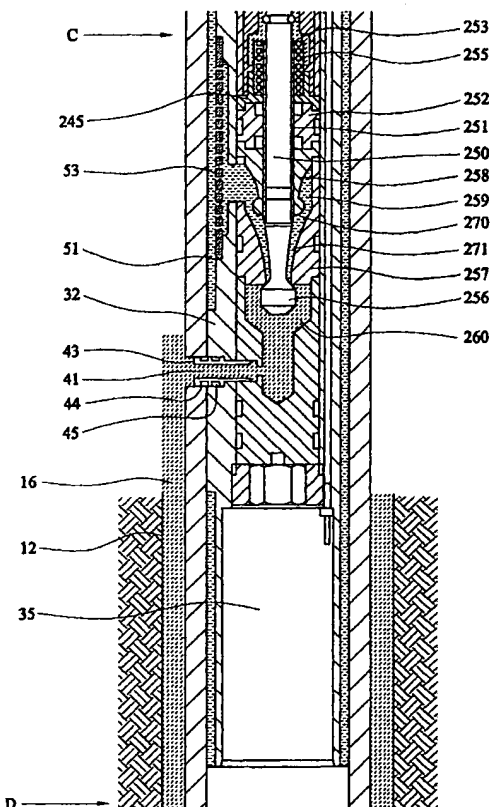
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(54) Title: A PRESSURE PULSE GENERATOR



(57) Abstract: A pressure pulse generator for use in MWD operations in a drilling installation (10) having a drillstring (11), a drilling bit (19), means (13, 14) for supplying drilling fluid via the interior of the drillstring (11) and to the drilling bit (19), and an annulus (16) between the drillstring (11) and the wall (12) of the borehole which is being formed, said pressure generator being operative to generate a pressure pulse signal in the drilling fluid, and to transmit such signal to pressure monitoring equipment (20, 21) at the surface, and in which the pressure pulse generator comprises: an outer housing (30) which can be mounted in a drillstring component, and in which the operating components of the pulse generator are housed; a main valve (256, 257) having a valve operating chamber which, when the valve is opened, allows drilling fluid to pass from the interior of the drillstring to the exterior, and thereby to generate a pressure pulse signal that will travel to surface; a first pilot valve (116, 120) which is normally open, to allow fluid in the operating chamber of the main valve to communicate with the drilling fluid in the annular; and, a second pilot valve (88, 89, 90) which is normally closed, to control flow of drilling fluid between the inside of the drillstring and the operating chamber of the main valve.

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A PRESSURE PULSE GENERATOR

This invention relates to a system of communication employed during the drilling of boreholes in the earth for purposes such as oil or gas exploration and production, the preparation of subterranean services ducts, and in other civil engineering applications.

Taking the drilling of oil and gas wells as an example, it is highly desirable both for economic and for engineering reasons, to obtain information about the progress of the borehole and the strata which the drilling bit is penetrating from instruments positioned near the drilling bit, and to transmit such information back to the surface of the earth without interruption to the drilling of the borehole. The generic name associated with such techniques is "Measurement-while-Drilling" (MWD). Substantial developments have taken place in MWD technology during the last thirty years.

One of the principal problems in MWD technology is that of reliably telemetering data from the bottom of a borehole, which may lie several thousand metres below the earth's surface. There are several established methods for overcoming this problem, one of which is to transmit the data, suitably encoded, as a series of pressure pulses in the drilling fluid; this method is known as "mud pulse telemetry".

In one means of generating pressure pulses at a downhole location, the fluid flowpath through the drill string is transiently restricted by the operation of a valve. This creates a pulse, the leading edge of which is a rise in pressure; hence the method is colloquially, although rather loosely, known as "positive mud pulse telemetry". In contradistinction the term "negative mud pulse telemetry" is used to describe those systems in which a valve transiently opens a passage to the lower pressure environment outside the drill string, thus generating a pulse having a falling leading edge. In a third basic method a continuous pressure wave is generated downhole and modulated with the information to be transmitted to the surface. It is to the second of the above methods, namely "negative pulse telemetry", that the present invention relates.

Good practice in the drilling of boreholes in the earth aims at keeping the diameter of the borehole as small as possible consistent with the mechanical strength and

stability of the drilling system and with the availability of ancillary equipment (such as MWD systems, motors, orienting tools, wireline logging tools, perforating guns and so on). The advantages gained in the saving of costs of drilling equipment, energy and materials, by drilling the smallest diameter borehole possible in any given set of conditions, are obvious. It will be understood that in the typical operation of drilling an oilwell, a series of coaxial boreholes, are drilled, each being lined with steel tubing before the drilling continues at a smaller borehole diameter. By making the diameter of the final section as small as is practicable, the diameters of the previous hole sections can also be reduced.

Continuing introduction of improved materials and equipment has led to a steady reduction in the typical diameter of borehole sections over time. It is nowadays relatively common to drill borehole sections of 3.5"-5.0" diameter whereas only a decade or so ago those same hole sections would have been in the diameter range 6.0" – 8.5". Furthermore it is now common practice to drill high angle or horizontal extensions from existing boreholes in oil reservoirs using equipment which will pass through the tubing in the existing well: this operation requires small diameter drilling equipment. The continuing demand for the drilling of smaller diameter boreholes has produced a corresponding demand for ever slimmer ancillary equipment such as MWD tools.

Because the present invention extends the applicability of "negative pulse" systems to very small diameter drilling equipment (drill strings down to 2.875" diameter), it is appropriate to comment briefly on the relative merits of "positive" and "negative" pulse systems. Although this terminology is inexact, as was explained above, it is well recognised in the drilling industry. Strictly speaking, the primary distinction is between "throttling" and "bypass" systems. In throttling systems a valve operates to contract or enlarge a restriction through which some or all of the drilling fluid passes on its way to the drill bit. In bypass systems a valve operates to allow a portion of the drilling fluid to pass from a relatively high pressure region inside the drill string to a relatively lower pressure region in the annular space between the drill string and the wall of the borehole. The pressure difference between the interior and exterior of the drill

string is created by the dynamic pressure losses as the drilling fluid passes through equipment situated below the MWD tool, such as drilling motors and the jets in the drill bit itself.

In the case of throttling control, the quiescent position of the throttling valve is naturally configured to be such as to minimise the restriction offered to the flowing drilling fluid: when the valve moves towards a closed position and returns to its starting point, a "positive" pulse is generated. In the case of bypass control the quiescent position of the bypass valve is naturally configured to be such as to minimise the loss of drilling fluid to the drill bit, namely the position in which the bypass orifice is closed. When the valve is opened and returned to its closed position, a "negative" pulse is generated.

On the basis of the above definition, the third type of pulse generator mentioned above, the continuous wave generator, is a throttling valve, since it operates wholly within the drill string and no fluid is bypassed. US Patent 4,641,289 discloses a method which generates both positive leading-edge and negative leading-edge pulses by causing a valve in the drill string to move in a controlled fashion from a mean position in either direction from its valve seat. Again because no fluid is bypassed, this is a throttling system as defined above.

The principal operational distinctions between throttling and bypass valves can be drawn as follows:

Throttling pulse generators require that the main valve parts are exposed to a continuous flow of drilling fluid. Relatively high forces are required to displace the moving part of the valve in the mud stream. Because all, or at least a large proportion, of the total drilling fluid flow has to pass the main valve, the performance limits of a throttling pulse generator are largely determined by the flow rate. The operational flow rate is determined in any particular case according to the drilling engineering requirements. Drilling fluid flow rates typically range from 200 litres/minute to 6000 litres/minute and it is necessary to design throttling pulse generators in a substantial number of different sizes to cover all possible drilling operations.

In bypass pulse generators the valve that generates the main pulse remains fully

closed except when generating a pulse and is not required to support continuous flow. This is a substantial advantage because the valve parts are protected from erosion by the solids-bearing drilling fluid for the majority of the operating period of the equipment. The rise time and eventual amplitude of the pulse are dependent not on flow rate but on the pressure drop between the inside and the outside of the drill string. This pressure drop is dependent on drilling engineering requirements and can vary from 2MPa to 200MPa. It is relatively easy to design a single bypass pulse generator that will handle this range of pressure drops, with only minor changes, such as altering the size of an external orifice to control the pulse amplitude. Because there is no direct performance dependence on the main fluid flow rate, a single design of pulse generator – with simple mechanical adaptation - can be used right across the size range of the drill string. The eventual lower size limit is reached when the space available in the drill string element around the pulse generator becomes too small to handle the required flow: but the flow rate required to support the drilling operation reduces roughly in proportion to the size of the hole being drilled, so that this factor does not becoming limiting until very small drill string diameters are reached. A further advantage of bypass pulse generators is that the valve parts may be small and of relatively low mass, so that fast valve operation can be achieved with little energy expenditure.

The present invention discloses a particularly efficient and flexible method of driving a main mud valve of the bypass type using twin pilot valves in which the working fluid is drilling the drilling fluid. The general principle of using pilot valves is of course well known, and existing applications of this technique in the MWD field fall into two main classes.

In the first class energy derived from the mud stream is used to maintain a source of clean working fluid, such as hydraulic oil at a suitable pressure to operate, under control of a small valve, a piston actuator driving the main mud valve. Examples of this type of device are described in US Patents 2,964,116, 4,184,545 and 4,535,429.

In the second class the working fluid is the drilling mud itself. Examples of this type of device are described in US Patents 3,958,217, 4,120,097, 4,742,948, 5,040,155,

5,333,686, 5,586,084 and 6,016,228.

The two main classes of actuation can be categorised in general as follows. Those that use a separate working fluid are relatively complex, with many parts co-operating in the processes of supplying and maintaining the pressure of the working fluid. Those that use the drilling fluid as the working fluid are relatively simpler in concept – since there is an unlimited supply of pressurised fluid available – but the relevant parts of the pilot mechanism must be capable of withstanding the aggressive and highly variable properties of the drilling fluid.

It is an objective of the present invention to provide a MWD pulse generator operated by pilot valves and in which the pilot working fluid is drilling fluid.

It is a particular advantage of the invention that it can provide a so-called "negative-pulse" MWD in tools of extremely small diameter: for example the entire pulse generator can be constructed for installation in a 2.875" diameter drill pipe. The ability to use negative-pulse MWD has certain advantages, mentioned in the comparative discussion above, which have not hitherto been realised in tools of this diameter.

It is another advantage of this invention that long working life between service operations can be obtained while retaining the simplicity of using the drilling fluid to operate the pilot system.

It is another advantage of this invention that the pilot valves may be constructed in such a way that their operations are hydraulically similar to each other and to that of the main valve. Thus all the design criteria including those of materials selection for handling the abrasive drilling fluid may be applied equally to the valves. The pilot valves are miniaturised versions of the main valve.

It is a further advantage of this invention that the energy required to provide each MWD pulse to surface is extremely small, making battery operation, with its attendant simplicity, feasible for long periods of time.

Yet another advantage of the invention is that the same central pulse generator may be utilised across the entire range of drill collar diameters from the smallest practical size upwards – without limit – as needed, simply by the addition of appropriate

spacers and mechanical adapters. Because several, usually at least three, different diameters of drill bit and associated drill collars are sequentially used in drilling a single borehole this adaptability of the pulse generator can substantially reduce the operational costs of the MWD equipment.

The general principle of the operation of the invention is as follows. A main valve chamber contains a piston-operated, spring-return poppet valve and seat. When this valve is opened, drilling fluid can pass from the interior of the drill string to the exterior, generating the signal pressure pulse that will travel to surface.

Two much smaller, electrically actuated pilot valves co-operate in supplying operating fluid, in this case drilling fluid, to the main valve piston. A first pilot valve is normally open, and allows fluid in the operating chamber of the main valve piston to communicate with the drilling fluid in the annulus. A second pilot valve is normally closed and controls operating fluid flow between the inside of the drill string and the operating chamber of the main valve piston.

The actuators for the pilot valves are immersed in hydraulic oil to prevent access of the particulate drilling fluid to the sensitive actuator parts. The hydraulic oil pressure is equalised by well-known means to the pressure of the drilling fluid in the borehole.

To actuate the main valve the following sequence of events is caused to take place at successive time intervals.

The first pilot valve is closed and disconnects the main valve piston from the low pressure drilling fluid in the annulus.

The second pilot valve is opened, allowing the access for high pressure fluid from the drill string to the main valve piston; the main valve consequently opens.

The second pilot valve is closed, leaving the main valve position unchanged.

After a selected time interval the first pilot valve is reopened, allowing the main valve operating chamber to vent to the lower pressure region of the annulus outside the drill string; consequently the main valve re-closes and the system is restored to its original state.

The principal advantages of this invention arise because each pilot valve can be

specifically designed for unidirectional flow, and the force needed to operate the pilot valves can be minimised. The closure of each pilot valve is performed under no-flow conditions. The opening of each pilot valve vents fluid in the preferred direction across the valve again allowing the operating force to be minimised. The small size of the valves and the hydraulic balancing mentioned above cause the required operating forces to be very low. The low operating forces and, as will be seen later, short operating travel of the valves not only lead to low energy consumption but also allow the operating actuators to be of very small diameter. This in turn permits the system to be constructed inside very small diameter drill pipe, as mentioned earlier.

Alternative operating means for similar systems are described in the prior art. For example, US Patent 4,401,134 discloses a means of low-energy operation in which the working fluid is hydraulic oil: two pilot valves, one electrically and one hydraulically operated co-operate in driving the main valve piston. But in this system the high-pressure working fluid supply has to be replenished by means of a regenerative pump. US Patent 5,586,084 describes a system in which the working fluid is the drilling fluid, controlled by an electrically operated pilot valve, but represents the latter by a conventional symbol without any disclosure of how such a valve may be made to perform reliably when controlling the flow of a highly particulate fluid such as drilling mud, nor of the energy requirements of the valve. Both of the above references describe systems which control a throttling valve, not a bypass valve such as is the subject of the present invention.

Description of a preferred embodiment of the invention

Figure 1 is a schematic representation of a drilling rig and MWD system to which the invention may be applied;

Figures 2a, 2b and 2c show a cross-sectional view of the pulse generator divided into three longitudinal sections;

Figures 3a and 3b show enlarged views of the part numbered 120 in figure 2b;

Figures 4a, 4b and 4c show details of a fluid filter designed to protect the pilot valves from particulate matter in the drilling fluid;

Figure 5 is a timing diagram illustrating the sequence of pilot valve operations

required to cause the pulse generator to provide one pulse;

Figure 6 shows an example of how the total current changes with time as the valve operating sequence progresses;

Figure 7 shows an example of how the cumulative energy consumed changes with time as the valve operation progresses.

A typical arrangement of a mud pulse MWD system is shown schematically in Fig. 1. A drilling rig 10 supports a cylindrical drill string 11 in the borehole 12. Drilling fluid, which has several important functions in the drilling operation, is drawn from a tank 13 and pumped, by pump 14, down the centre of the drill string, shown cutaway at 15, and returning by way of the annular space 16 between the drill string and the borehole wall 12. The part of the drill string 18 near the drill bit 19 houses MWD equipment that includes a means for generating pressure pulses in the drilling fluid. The pressure pulses travel up the centre of the drill string, and are received at the earth's surface by a pressure transducer 20. Processing equipment 21 decodes the pulses and recovers the data that was transmitted from downhole.

Referring to Figures 2a to 2c, the MWD pulse generator consists of the contents of the generally cylindrical housing 30, mounted in the cylindrical drill string element 18. Ribs at 31 and 32 provide a means to support the housing 30 in the drill string. These ribs are permanently secured to, or an integral part of, the housing 30, and extend longitudinally as illustrated. There are several ribs disposed circumferentially around the housing at these points.

Drilling fluid flows past the pulse generator through the space 34 – shown in Fig 2 with horizontal-dash hatching - which is generally annularly disposed around the housing 30 except in the regions where the ribs at 31 and 32 contact the drill string element 18. The drill string element 18 is of course wholly surrounded by the annular space 16 by way of which the drilling fluid returns to surface: but for clarity of the drawing only a small section of the borehole wall 12 is shown, in Fig 2c.

The orientation of the pulse generator in the drill string is not relevant to its operation. Solely for the purposes of illustration and description it will be assumed that

the part at the top of Figure 2a is uppermost and the part at the foot of Figure 2c is lowermost.

It will be understood that the other parts of the MWD system, including a supply of electrical energy, instruments for measurement of the parameters to be transmitted to surface and electronic equipment for conversion and encoding of the data for transmission are also mounted inside the drill string and may be connected to the pulse generator housing 30 at either or both of the ends 35 and 36: but because such equipment is well-known and is not the subject of the present disclosure, it will not be described in further detail. It should be noted however that a number of electrical connections may be provided between the housing ends 35 and 36, one of which is shown at 37. These connections may be run in insulated wires in long bores in the outer housing 30.

The ribs at 31 and 32 provide physical centralisation for the housing and also permit access between the interior of the pulse generator and the drilling fluid in the annular space 16 by way of the ports 40 and 41 which are formed in the locking bolts 42 and 43 respectively and sealed from the interior of the housing 30 by O-rings 44 and 45 respectively. Each of the several ribs in each of the circumferential locations indicated by 31, 32, carries a separate bolt and port as described above. The housing 30 also has milled recesses 50 and 51 in several circumferentially disposed places at each location, into which are fitted filter elements 52 and 53 that allow access between the drilling fluid flowing through the drill string and the interior of the pulse generator. The filter elements at 52 and 53 are indicated merely symbolically on Fig 2; the actual details of their construction will be described later.

The access ports, filters and stabilising ribs described above may of course be disposed around the circumference of the housing 30 in any suitable number and at any angular separation: but it is preferred to have three of each set at 120° intervals. This arrangement is convenient for manufacturing and ensures that when the housing lies in an inclined borehole there is free access for fluid to at least two of the sets of ports even if the third is partially obstructed by contact with the earth formation being drilled.

It will be apparent that the radial length of the ribs 31, 32 and of the bolts 42, 43

may be varied to enable the pulse transmitter to be housed in drill collars of diameters other than that shown. The ribs may be extended simply by attaching spacers to them with screws or other fasteners, thus permitting a single transmitter to be used over a wide range of drill collar internal diameter.

An additional separate port 60, formed in plug 61 allows access between the drilling fluid in the annular space between the drill string and the borehole and the interior of the pressure pulse generator for ancillary purposes to be described later. As will be seen, this port is essentially required only to be maintained at the borehole pressure and therefore it is not replicated elsewhere on the circumference of the housing 30.

Within the pressure pulse generator there are three principal regions, which have been denoted by letters in Figures 2a to 2c. They are: the pressure switch region A-B, the pilot valve region B-C and the main valve region C-D.

In the pilot valve region there are four inner housings: the upper pilot valve housing 80; the pilot chamber housing 110; the lower pilot valve housing 140 and the balancing piston housing 170. These four housings are interconnected sealably each with the next and for the purposes of understanding the operation of the overall system they can be regarded as a single inner housing, sliding into the main housing 30 and carrying a number of internal bores, cross-bores, seals and fluid access passages. Their division into the separate parts enumerated above is necessary to make assembly and maintenance practical.

Within housing 80 there is an electromagnetic solenoid actuator consisting of yoke 81, armature 82, coil 83 and casing 84. Armature 82 carries a valve stem 85 with ball poppet head 86. The spring 87 biases the armature 82 to be at its maximum distance from yoke 81 when coil 83 is not carrying current. The metal parts 81, 82 and 84 are made from any suitable magnetically soft material. The valve parts 85 and 86 extend downwards into the valve chamber housing 110.

Within housing 140 there is an electromagnetic solenoid actuator consisting of yoke 111, armature 112, coil 113 and casing 114. Armature 112 carries a valve stem 115

with ball poppet head 116. The spring 117 biases the armature 112 to be at its maximum distance from yoke 111 when coil 113 is not carrying current. There is a further spring 118 in this assembly, the purpose of which will be described later. Valve parts 115 and 116 extend upwards into the valve chamber housing 110.

Within housing 110 there are also the remaining parts of the upper and lower pilot valve assemblies. Valve guide 88, sleeve 89 and seat 90 complete the upper pilot valve: there is a seal 91 dividing the valve region from the actuator region. Valve guide 119 and seat 120 complete the lower pilot valve: there is a seal 92 dividing the valve region from the actuator region.

It will be noted that the valve head 116 and seat 120 form a valve which is open to fluid flow when the actuator coil 113 is not carrying current. When coil 113 is energised, valve head 116 moves to close against seat 120. However if valve stem 115 and valve head 116 were rigidly attached to armature 112, it would be impossible in practice to ensure that the valve head 116 could meet the seat 120 and simultaneously that the contact face of armature 112 could meet the corresponding face of yoke 111. If the first only of these conditions was satisfied there would be a residual gap between yoke 111 and armature 112, leading to a requirement for greater current in coil 113 to hold the valve closed than would be the case if the actuator yoke and armature were in contact. If the second only of the conditions was satisfied there would be a residual gap between the valve head 116 and seat 120. To overcome this difficulty the spring 118, partially precompressed to exert a force greater than that exerted by spring 117 in its compressed state, is fitted to provide compliance between the armature 112 and the valve stem 115. The assembly is built so that the valve and seat will always contact each other before the gap between the yoke and armature closes. Then spring 118 is moved into further compression and the faces of the yoke and armature meet. The spring 118 also acts to take up any slight wear which may take place in the poppet head and valve seat during operation.

Continuing the description of operation, drilling fluid from the region within the drill string communicates with upper pilot valve 86/90 via filter 52, ports 121, 122, 123

and valve chamber 130. Drilling fluid at the lower annular pressure communicates with lower pilot valve 116/120 via port 40 in the bolts 42, ports 124, 125 and valve chamber 126.

It should be noted in relation to the ports 121-125 inclusive mentioned above, that they form a communication path for fluid through several concentric elements of the tool, namely the main housing 30, the valve chamber housing 110 and the parts of the upper and lower valve bodies 89 and 120 respectively. Although, as will be explained later, the quantity of fluid which traverses these passages at each valve operation is very small, it is nonetheless important to minimise the restriction to the flow of the fluid. It is preferable to provide several radial ports, suitably spaced circumferentially in each of these locations.

Additionally, to avoid the need for exact lining up of the various parts which constitute each port, a semicircular groove is milled circumferentially in each of the concentric parts through which the ports pass. The groove 127 is an example, and it will be apparent from the drawing where the other similar grooves are located. Figure 3a shows a perspective view, and Figure 3b a sectional view, of the valve guide 120, with groove 127 and radial ports 129 indicated, to illustrate this concept.

It is necessary that the zones in the concentric parts through which the ports 121 – 125 pass, and many other mutually adjacent zones of the entire assembly, must be sealed one from another. The solidly blocked regions of Figure 2, for example 128, all indicate sealing elements. Such seals are typically O-rings made of Viton material that may also have support rings on the low pressure side made from Teflon or a derivative thereof: or for seals which are required to withstand severe pressure differentials they may be square-section rings with appropriate supports. Such seals and the techniques for applying them are very well known, and they will not be described further.

A chamber 141 is in communication with both the upper and the lower pilot valves. The chamber 141 also communicates via several cross-bores 145, of which only one is shown, by dotted lines, with an annular space 146 formed between the housing 30 and the housings 140 and 170, the latter two parts being coaxial and sealably

interconnected. This annular space in turn communicates through bores 171 with the volume 172.

Connected to the volume 172 are two further elements of the system. One of these is piston 200, the function of which will be described later. The other is the main valve stem 250, which, together with a sleeve 251, also forms a piston running in guide 252. It will be noted that the effective diameter of this piston is the diameter of the sleeve 251. Ancillary parts 253, 254 and spring 255 cause the poppet head at the end of valve stem 250 to be held closed against the seat 257 in quiescent conditions. A fluid deflector 258 with a nib 270 both serves to protect the valve stem 250 from erosive wear where it emerges into fluid chamber 259 and has a function in controlling the pressure regime in the downstream part 271 of chamber 259.

Drilling fluid in the annular space between the drill collar 18 and the main housing 30 has access to the poppet valve 256/257 through filters 53 and chamber 259. The discharge from the poppet valve, when it is actuated, passes through valve chamber 260 and ports 41 to the annular space between the drill collar 18 and the borehole wall 12.

As mentioned above, volume 172 also communicates with piston 200. Volume 172 is connected to pilot valve chamber 141 by the cross-bores 145 and annular space 146, as described earlier; thus the pressure in volume 141 follows that in volume 172, with a slight time lag. The purpose of piston 200 is to provide pressure equalisation, whilst separating the fluids concerned, between the drilling fluid in volume 172 and hydraulic fluid, which may be any low-viscosity mineral oil suitable for the temperature range required, contained in volume 300 and in all other spaces connected to that volume. The regions containing hydraulic oil are shown in dotted shading in the drawing, and communication between these spaces is provided by a series of bores and passages. The selection of the configuration of these bores is a matter of convenience and will not be described in detail, however it should be noted in particular that the hydraulic oil surrounds all the elements of the electromagnetic actuators described earlier and is also provided to the chamber 290, the purpose of which will be described later.

The provision of hydraulic oil at the drill-pipe pressure to the actuators ensures defined pressure conditions on the stems of the poppets 85 and 115, and the oil acts as lubricant for the high-tolerance machined parts of the actuators. The length of housing 170 is made sufficient to maintain piston 200 clear of the ends of the housing over the anticipated range of change in the volume of hydraulic oil caused by changes in temperature and pressure, as is well known in this type of downhole tool. The oil fill is introduced into the system prior to use by evacuation and filling through the port 295, which is subsequently closed by plug 296: this again is a well-known technique.

It was mentioned above that hydraulic oil at drill-pipe pressure is also provided to chamber 290. This chamber communicates with one face of piston 291. The other face of piston 291 communicates with the drilling fluid in the borehole via port 60. The purpose of piston 291 and the associated unlabelled parts is to close electrical contacts 292 when the differential pressure between the fluid in the drill string and that in the borehole reaches a predetermined level. This switch is used for control purposes in the other parts of the MWD system and has no direct relevance to the present invention, being briefly described here for completeness. Other well-known methods are available to provide this control function.

Turning in more detail to the operation of the invention, it can be seen that the pressure in the chamber 141, which is under the control of the pilot valves consisting of poppets and seats 86/90 and 116/120 respectively is communicated to the piston chamber 172 of the main valve 256/257, and that when the pressure in this chamber is sufficiently raised the valve stem 250, together with its sleeve 251 will move forward, opening a gap between poppet head 256 and seat 257. Drilling fluid now flows from the drill string into the pulse generator through the filter 53 and out to the borehole through ports 41. This causes the pressure in the drill string in the region of the pulse generator to fall. When the valve is allowed to reclose after a short time interval, the pressure in the drill string in the region of the pulse generator is re-established to its original level. The pressure changes are propagated up the drill pipe to the equipment at the surface of the earth, where they are detected as a pulse with a negative-going leading edge. This procedure, and the

details of encoding and decoding of the data for transmission to surface are not of direct relevance here, and will not be further described.

To create the conditions necessary for the valve 256/257 to open, a sequenced operation of the pilot valves is caused to take place. The sequence is initiated according to the requirements for the transmission of coded data and controlled by a processor or other electronic logic devices using conventional methods.

Firstly, the coil 113 is energised and the lower valve poppet 116 moves against the seat 120. During this operation a very small quantity of hydraulic oil is displaced by the movement of armature 112 into the general volume of oil surrounding the actuator, via the oilway 281. Suitable dimensions for the parts involved are that the diameter of the poppet valve stem may be 2.5mm and the stroke length may be between 2.0 and 2.5mm: thus the maximum oil displacement during the motion of the valve stem amounts to about 12 cubic millimetres. The piston 200 may have a diameter of 19mm and it can readily be calculated that the displacement of 12 cubic millimetres of oil will cause a linear movement of the piston of about 0.04mm. In practice, because this movement is so small, the piston simply "rocks" on the seal. The point is important, because the differential pressure required to move the piston and its seal together, relative to the bore of cylinder 170, against frictional forces would substantially and adversely affect the force required from the actuator to move the valve stem 115. This principle obtains for each subsequent movement of both of the pilot valves and will not be described repeatedly.

At this stage in the sequence, the chamber 141 has been isolated from the fluid in the borehole.

Next the coil 83 is energised, causing the upper valve poppet 86 to move away from the seat 90. Now drilling fluid can flow from the interior of the drill string 18 through the filter 52, the ports described earlier and the valve seat 90 into the chamber 141. The rise in pressure in chamber 141 is communicated to the main valve piston chamber 172 through the ports previously described, and the main valve opens.

Next the coil 83 is de-energised. At this point no flow is taking place through the

valve seat 90, and the poppet head 86 returns to its original position under the influence of spring 87. The chamber 141, and hence the chamber 172, are once more isolated from the drilling fluid, and the main valve will remain open for as long as this condition continues. During this phase of the pulse the only energy being consumed is that required by the coil 113 to maintain the lower pilot valve poppet 116 against its seat.

Finally the coil 113 is de-energised and the valve head 116 return to its original position under the influence of spring 117. Fluid leaves chamber 141 and returns to the borehole via the valve seat 120, the ports described earlier and exit ports 40. The main valve piston now returns to its original closed position under the influence of spring 255.

The sequence described above is illustrated in Figure 5 in the form of a valve timing diagram. The actual times shown are chosen for illustrative purposes only. Changes in timing over a wide range are possible and other timings may be used to suit specific operational circumstances.

The timing diagram shows an operational sequence for a main valve operation in which it is assumed that current is applied to the actuator for valve 116 starting at $t=20$ milliseconds. Valve 116 closes. No change takes place in the condition of the system overall, other than the displacement of a very small volume of the hydraulic oil fill as the valve stem 115 moves.

After a period long enough to ensure that valve 116 is fully closed, current is applied to the actuator for valve 86. Valve 86 opens and drilling fluid flows through it to open main valve 256 as described earlier.

In principle, valve 86 may be re-closed as soon as main valve 256 is fully open. In practice it is desirable to leave a safety margin to ensure that pressure conditions are fully settled and that there will be no residual differential pressure between the drilling fluid in the drillstring and that in the main valve operating chamber. By way of example only, a period of approximately 140 milliseconds is shown.

At a later time, shown in this example as $t = 420$ milliseconds, valve 116 is re-opened, allowing the fluid from chamber 172 to return to the annulus and the main valve 256 to re-close. The system is now once again in the quiescent state, having been open

for a period of approximately 400 milliseconds.

During the generation of each pressure pulse, as described above, some drilling fluid flows into the pilot system from the drill string and returns to the borehole. There is a potential problem when using drilling fluid as the hydraulic working fluid, which is that the abrasive and solids-bearing nature of typical drilling fluids might have an adverse effect when used in a system with small clearances and passages, such as the present invention. The practical means of dealing with this potential difficulty are important to the overall function of the invention and will now be described.

Firstly, the volume of drilling fluid handled by the pilot valve system for each pulse is extremely small. It is defined by the diameter of the sleeve 251 of the main valve stem and the stroke of the valve stem. Practical dimensions can be for example that the valve sleeve diameter is 12mm and the stroke 3mm. The volume of fluid which traverses the pilot valves for each pulse generated may be calculated as being less than 0.5 ml. In practice the volume is a little larger because of the compliance of the fluid itself and of the various seals, but can be maintained at under 1ml without difficulty. A typical MWD system may be required to generate of the order of 10^5 pulses in the course of a single downhole trip lasting for several days. In such conditions the total volume of drilling fluid which the pilot system is required to handle is only 100 litres.

Secondly it may be noted that the volume of the main piston chamber 172 and its associated feed ports is very much greater than the volume of drilling fluid handled at each pulse. Drilling fluid never has to pass through the main valve chamber: it is in effect shuttled into and out of the chamber 141 and a part of the communicating ports 145. The fluid in chamber 140 is subjected only to pressure changes, not to the passage of abrasive fluid, and it may therefore be filled with a benign fluid (such as a high temperature silicone grease, or a high viscosity silicone oil) prior to operations.

Thirdly, the role of the filters 52 is clearly important in ensuring that particulate matter larger than the internal clearances cannot enter the system. To this end the filters may be configured as shown in Figures 4a, 4b and 4c. Figure 4a shows a transverse cross-section of the filter element 52. Figure 4b is a view of the inlet side of the filter and

figure 4c shows the outlet side, that is, the side presented to the interior of the pulse generator. Very narrow longitudinal slots 400 are cut in such a way that any material passing the slot will assuredly exit through the wider passages 401. A suitable width for these slots is 0.25mm. It is re-emphasised that these filters, in a typical situation, have the repetitive task of handling only 1ml of entering drilling fluid at a time, and the total task of handling a flow which may average less than 1 litre per hour.

A possibility exists that material such as irregularly shaped sand particles may be trapped on the inlet side of the filter slots. Under these circumstances there is an increased erosion rate of the filter material in the neighbourhood, due to the effect known colloquially as "washing", in which a scouring effect caused by irregular turbulence downstream of a flow obstruction causes locally intense erosion. This "washing" tends first to widen the entry slot immediately downstream of the obstruction, which is thereby released into the main flow. Tests conducted with sand-bearing fluid have shown that this mechanism operates effectively. After a period of operation under these conditions inspection of the filter elements reveals some trapped particles and some slightly widened regions whence previously trapped particles have escaped. The other safeguard which is employed is that the total area of the filter slots is such as to keep the fluid velocity through them extremely small and thus minimise the occurrence of trapped particles.

The filter 53 may be similarly constructed, with its dimensions suitably scaled to be compatible with the clearances in the main valve and its associated ports.

Filters 52 and 53 are both considered to be wear parts, to be replaced as determined by the results of a visual check carried out in between downhole operational periods.

It was mentioned earlier that the similar nature and configuration of the main valve and the two pilot valves allows them all to be designed using common principles and materials. As is well known in this art, the parts of valves that handle abrasive drilling fluid, in this case the stems and poppets 250/257, 115/116 and 85/86 together with the valve seats 257, 90 and 120 may conveniently be made from tungsten carbide or other similar hard material.

The methods by which the energy consumption of this embodiment of the invention are minimised will now be described.

Firstly it will be noted that piston 200 essentially equalises the pressures in piston chamber 172 and the hydraulic oil which surrounds the pilot valve actuators. The pressure in chamber 172 is therefore communicated to the region of the valve stems 85 and 115 on the oil side of their respective seals 91 and 92. Taking each of the valve operations described above in turn:

At the time that the valve head 116 is required to move to the closed position, the pressures on both sides of the seal 92 are equal: provided that the areas of the shaft at the seal and of the valve seat are equal there is no net hydraulic force on the valve stem. The actuator only has to do work against the force exerted by the spring 117, the frictional force due to the valve seal and, just prior to closure, against force created by the wear take-up spring 118, the function of which was described earlier. Once the armature of the actuator has completed its movement, the current passing through coil 113 may be reduced to a much lower value, because the two faces of the actuator yoke and armature are now in contact with each other. This current reduction may be provided by well-known electronic means, either after the passage of a certain time or by detection that the movement of the armature is complete, using known methods such as that described by Scherbatskoy in Canadian Patent 1, 177, 948. Once the valve is closed, the pressure feedback provided by piston 200 ensures again that the net hydraulic force across the valve remains substantially at zero.

Before the valve head 86 moves from the closed to the open position the hydraulic pressures across the valve are equal, because chamber 141 remains at the same pressure as the hydraulic oil on the actuator side of the seal 91. The actuator initially only has to work against the spring and then against the flow force (tending in a direction to re-close the valve) as the small volume of drilling fluid passes the valve as described earlier. Now the pressure in chamber 141 rises to that of the fluid in the drill pipe, that pressure again being communicated to the actuator side of valve 86/90 and reducing the net hydraulic force across that valve to zero. As in the case of the valve 116/120,

described above, the current in coil 83 may now be reduced to the level that is required just to maintain armature 82 in contact with yoke 81 against the force of spring 87.

It should be readily apparent that the sequence described above occurs again during the events which lead to the closure of the main valve. When coil 83 is de-energised, valve head 86 closes under no-flow conditions under the influence of spring 87, and the pressures across the valve remain equal. Finally when coil 113 is de-energised, valve head 116 reopens by the influence of spring 117 under conditions essentially identical to

those that prevailed during the opening of valve 86, as described above, the pressures on both sides of the valve remaining substantially equal throughout.

Figure 6 shows, by way of example only, how the current flowing through the actuator coils changes with time during an operating sequence timed in the same manner as that described above. The time taken for each actuator to operate, measured from the time of application of current, depends on a number of factors including the current capability of the power supply, the inductance and resistance of the winding, the temperature of the winding and the total mechanical load on the actuator shaft. In this example it is assumed that the actuator is driven from a capacitor-discharge circuit such as that described by Scherbatskoy in U S Patent 4 839 370. With this type of drive the system is generally designed so that operation is completed well inside a period of 20 milliseconds, after which the main current is cut and a much lower current is sufficient to maintain the actuator in the energised condition. In Figure 6 the two current peaks represent the current supplied for the initial operation of each actuator. During the period when both actuators are in the energised condition (from $t = 80$ to 200 milliseconds in Figure 6) the hold-in current is doubled. Wide variations of design are practical, but in the example shown in Figure 6 the coil has a resistance of around 12 ohms and a de-energised inductance of around 30mH. Each actuator is driven from a 1000 microfarad capacitor pre-charged to 34 volts and under these conditions the current reaches a maximum of around 2 amperes in each actuator coil. Actuation is normally complete within 10 milliseconds. The current required to maintain each actuator in the energised

condition is only about 50 millamperes if an efficient switch-mode power supply is used.

Figure 7 is a representation of the cumulative energy consumption during the course of a single operating cycle. With parameters as indicated above, the operation of the two actuators consumes about 1.2 joules. During the period when both actuators are held in a further 0.4 joule is used. The change in slope at $t = 200$ milliseconds occurs when the first actuator is released. At the end of the cycle the total energy consumption is just over 2 joules per generated pulse. In battery powered MWD systems using, as is commonplace, lithium/thionyl-chloride batteries, it is straightforward, without using a disproportionate amount of space in a downhole system, to make 10^6 joules available to drive a pulse generator. Thus the required downhole lifetime of 10^5 pulses can readily be achieved.

The above description applies to the case where the effective areas of the valve seats 90, 120 are the same as those of their respective valve stems 85, 115 where they cross the seals 91, 92 respectively. In an advantageous variant of the embodiment described above, additional small imbalances in the forces across certain of the valves created by inequalities in the relationship between the diameter of the valve seats and the diameters of their respective valve shafts may be used to improve the efficiency of operation. Consider the quiescent (closed) state of valve 86 and seat 90. Let the seat area be A_1 and the shaft area A_2 . Let the pressure of the fluid in the drill string be P_d and that of the fluid in the annulus of the borehole P_a . The pressure P_a appears in the chamber 141 and at the actuator side of the shaft 85. The pressure P_d appears in the chamber 130. The hydraulic force on shaft 85 in the direction towards seat 90 is $(P_d - P_a)(A_1 - A_2)$. In any circumstances in which the transmitter is capable of generating a pulse, $(P_d - P_a)$ is positive. Thus the direction of the force on shaft 85 due to differential pressure will be in a direction tending to keep the valve closed if $A_1 > A_2$ and in a direction tending to open the valve if $A_1 < A_2$. There are of course other static forces, principally that due to the spring 87, but only the hydraulic forces are immediately relevant here. Thus by a suitable choice of the relative diameters of shaft 85 and seat 90 the net force required to open the valve may be made to increase or decrease, or remain unchanged, as differential pressure

risers.

When the valve head 86 is initially lifted from its seat it is immediately acted on by a flow force in a direction tending to re-close the valve. The initial flow rate, and hence the force, will increase as the differential pressure increases. If the combination of the actuator, the spring and other elements of the valve is designed to minimise electrical energy consumption at low differential pressures, then at some higher differential pressure, the valve may fail to open properly because of the increased flow force tending to re-close it. This is a transient effect which arises when the valve is "cracked" open and the actuator is near the beginning of its stroke, where the operating force is much reduced. If the actuator is designed to deal with the maximum differential pressure anticipated, then energy will be wasted at the lower differential pressures. However by taking advantage of the mechanism described above, the valve can be designed so that the increasing differential pressure acts to compensate hydraulically the effect of the increased flow forces by slightly reducing the net force keeping the valve closed. The forces involved are small, but significant. Small electromagnetic actuators are intrinsically limited in capability by constraints on iron cross-section and copper volume, and further constraints are caused by the need to operate at the high temperatures prevailing in many boreholes. For example in this preferred embodiment, the actuator is 25mm in overall diameter, and the areas of the shaft and seat differ by only about 0.5 mm². This is sufficient to provide a change in operating force of the order of 1kgf when the differential pressure changes by 20 MPa, representing about 20% of the initial force capability of this particular actuator.

During an operational period of the mud pulse transmitter it is inevitable that there will be small changes in operating forces caused for example by the bedding-in of seals and temperature changes. In the area of the valve heads and seats small dimensional changes occur caused by the erosive effect of fluid flow and by the impacts between the operating parts of the valves. It is customary, when such changes in operating characteristics are expected, to build in a safety margin, which might perhaps be to design the electromagnetic actuator and its associated circuitry to provide 50% more

initial force than is actually needed. Clearly some operating margin is required: but by using the hydraulic compensation described above that margin, and hence the quantity of electrical energy required to deliver each pulse, may be minimised.

The same hydraulic compensation principle may be applied to the pilot valve 116/120. But conditions are now slightly different, in that the valve closes under no-flow conditions, and re-opens by the action of the spring 117. The available force from the spring is of course at a maximum at the beginning of the stroke, and the need for compensation is less. In practice it has been found that the saving in energy achieved by compensating this valve is negligible in comparison with the normal minor variations from unit to unit.

Turning to the main valve 256/257, the objective is to maintain the valve operating conditions stable over a wide range of conditions.

When the main valve is closed, the pressures in the chambers 172 and 260 are equal and at P_a . The pressure in chamber 259 is P_d . If the areas at the seat 257 and the shaft 250 are equal, there is no net hydraulic force on the valve stem, and the valve is held closed by force exerted by the spring 255. The valve is opened by the pressure in chamber 172 rising to P_d , as described earlier. For a brief period of time, the entire force developed by the differential pressure ($P_d - P_a$) across the area of the sleeve 251 is available to overcome friction and initial flow forces as the valve opens.

Thereafter, the pressure regime is as follows. The pressure in the chamber 172 remains at P_d . The pressure in the region 259 becomes slightly less than P_d because of the pressure drop across filter element 53. The pressure in region 271 becomes substantially lower than P_d because of the pressure drop created across the nib 270 by the fluid flowing from chamber 259 past the valve head 256 and out through ports 41. The pressure in region 271 will be referred to as $P_d(-)$. Forces caused by fluid flow are exerted on the valve head 256, but are substantially cancelled out because of the quasi-spherical shape of the valve head. The actual flow rate which occurs for the two pressures P_d and P_a may be controlled by appropriate selection of the diameter of the ports 41, this selection being made to cover a broad range of expected values of $(P_d - P_a)$

before the equipment is placed in the wellbore.

CLAIMS

1. A pressure pulse generator for use in MWD operations in a drilling installation (10) having a drillstring (11), a drilling bit (19), means (13, 14) for supplying drilling fluid via the interior of the drillstring (11) and to the drilling bit (19), and an annulus (16) between the drillstring (11) and the wall (12) of the borehole which is being formed, said pressure generator being operative to generate a pressure pulse signal in the drilling fluid, and to transmit such signal to pressure monitoring equipment (20, 21) at the surface, and in which the pressure pulse generator comprises:

an outer housing (30) which can be mounted in a drillstring component, and in which the operating components of the pulse generator are housed;

a main valve (256, 257) having a valve operating chamber which, when the valve is opened, allows drilling fluid to pass from the interior of the drillstring to the exterior, and thereby to generate a pressure pulse signal that will travel to surface;

a first pilot valve (116, 120) which is normally open, to allow fluid in the operating chamber of the main valve to communicate with the drilling fluid in the annular; and,

a second pilot valve (88, 89, 90) which is normally closed, to control flow of drilling fluid between the inside of the drillstring and the operating chamber of the main valve.

2. A pressure pulse generator according to claim 1, in which the first and second pilot valves are electrically actuated valves.

3. A pressure pulse generator according to claim 2, in which the actuators for the first and second pilot valves are arranged to be immersed in hydraulic oil to prevent access of the particulate drilling fluid to the sensitive actuator parts.

4. A method of generating pressure pulse signals in a drilling fluid which is being supplied to a drilling installation (10) having a drillstring (11), a drilling bit (19), means (13, 14) for supplying drilling fluid via the interior of the drillstring (11) and to the drilling bit (19), an annulus (16) between the drillstring (11) and the wall (12) of the

borehole which is being formed, and a pressure pulse generator installed in the drillstring;

in which the pressure generator comprises an outer housing (30) which is mounted in a drillstring component, and in which the operating components of the pressure pulse generator are housed;

a main valve (256, 257) having a valve operating chamber which, when the valve is opened, allows drilling fluid to pass from the interior of the drillstring to the exterior, thereby to generate a pressure pulse signal that will travel to surface;

a first pilot valve (116, 120) which is normally open, to allow fluid in the operating chamber of the main valve to communicate with the drilling fluid in the annulus; and,

a second pilot valve (88, 89, 90) which is normally closed, to control flow of drilling fluid between the inside of the drillstring and the operating chamber of the main valve;

in which a pressure pulse signal is generated in the drilling fluid by the following steps:

actuating the main valve (256, 257) through a sequence of events at successive time intervals;

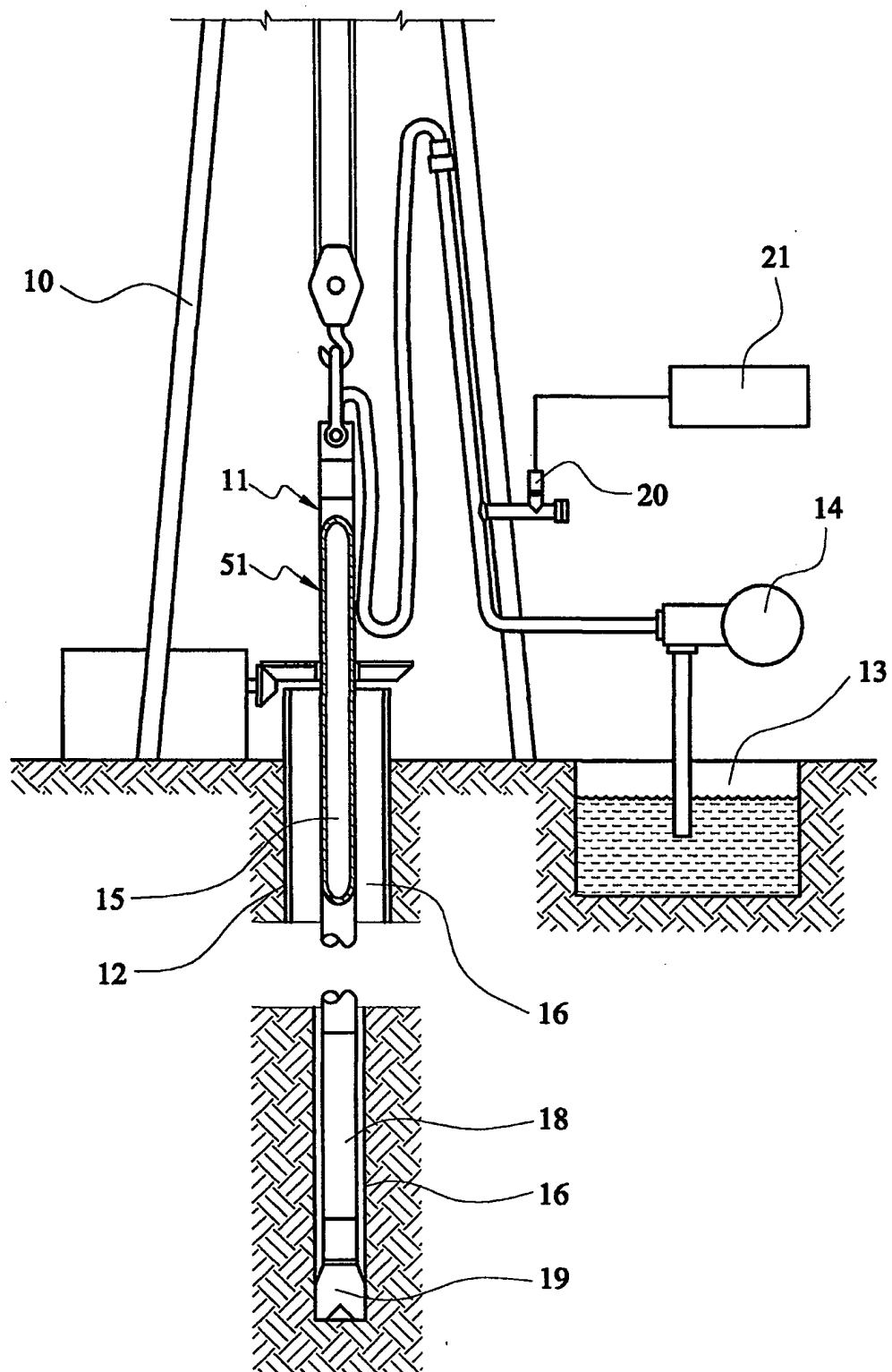
closing the first pilot valve and disconnecting the piston of the main valve from the flow pressure drilling fluid in the annulus;

opening the second pilot valve, allowing access for high pressure fluid from the drillstring to the main valve piston, whereby the main valve consequently opens;

closing the second pilot valve, leaving the main valve position unchanged;

after a selected time interval reopening the first pilot valve, allowing the main valve operating chamber to vent to the lower pressure region of the annular outside the drillstring, and consequently the main valve reclosing and the system being restored to its original state.

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**FIG. 1**

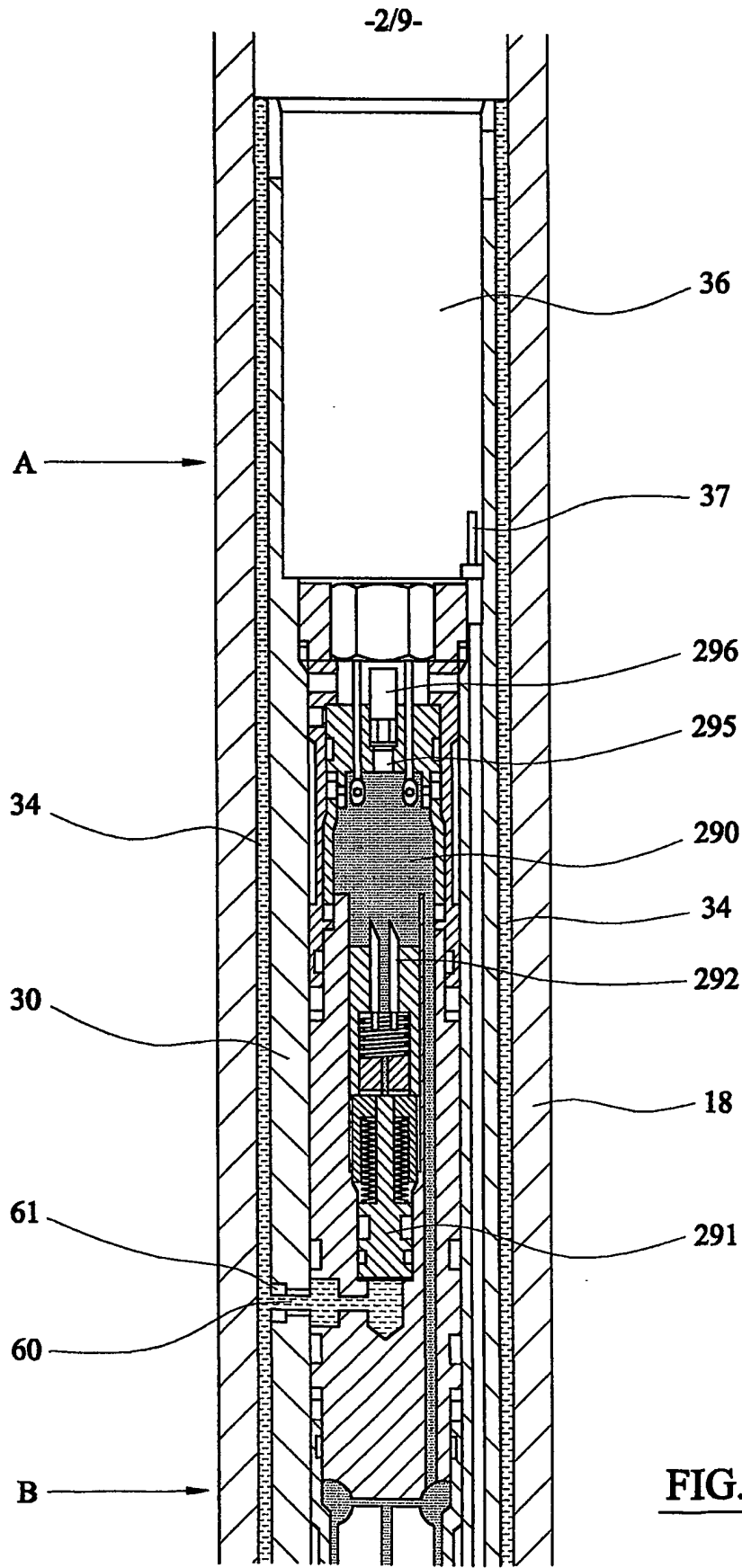


FIG. 2a

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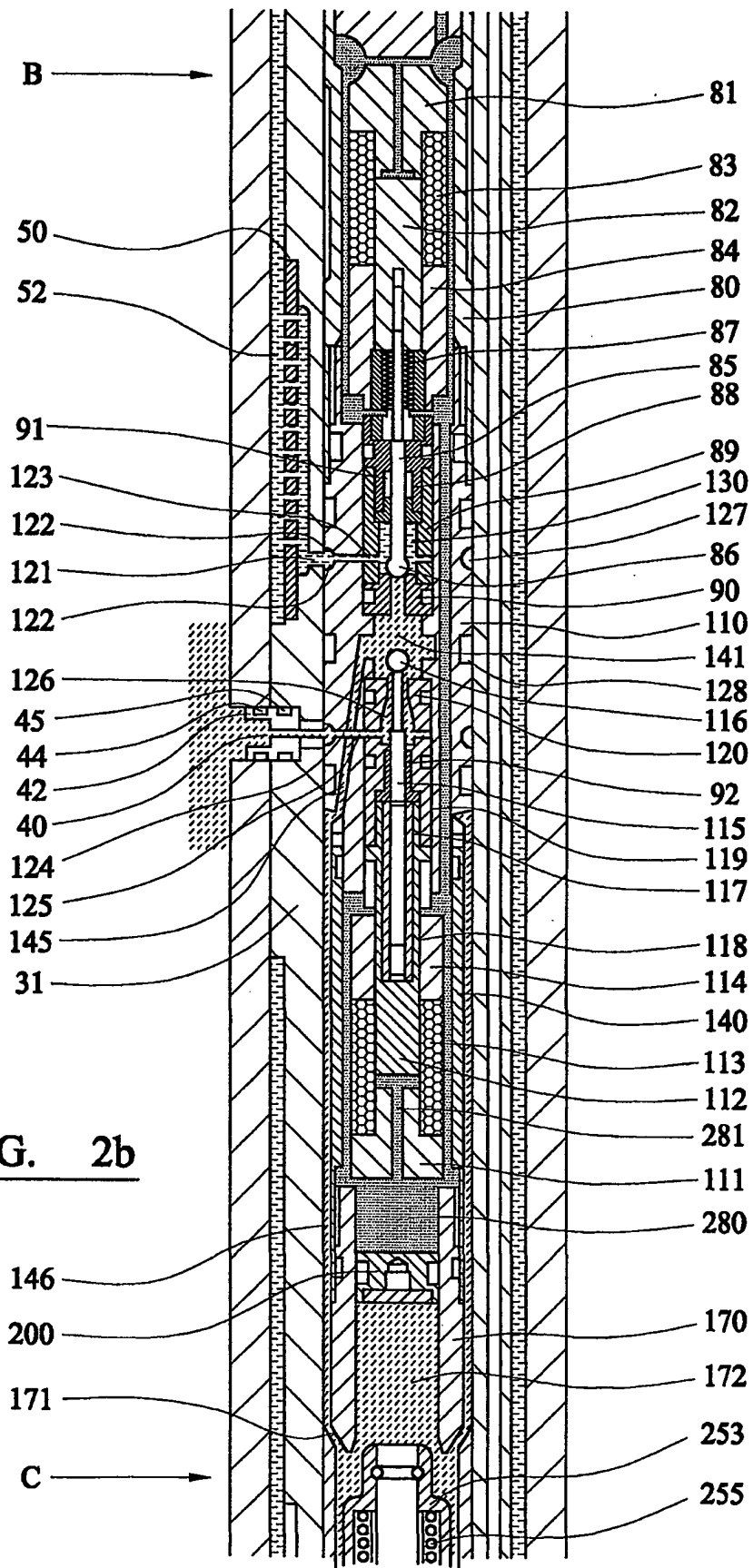
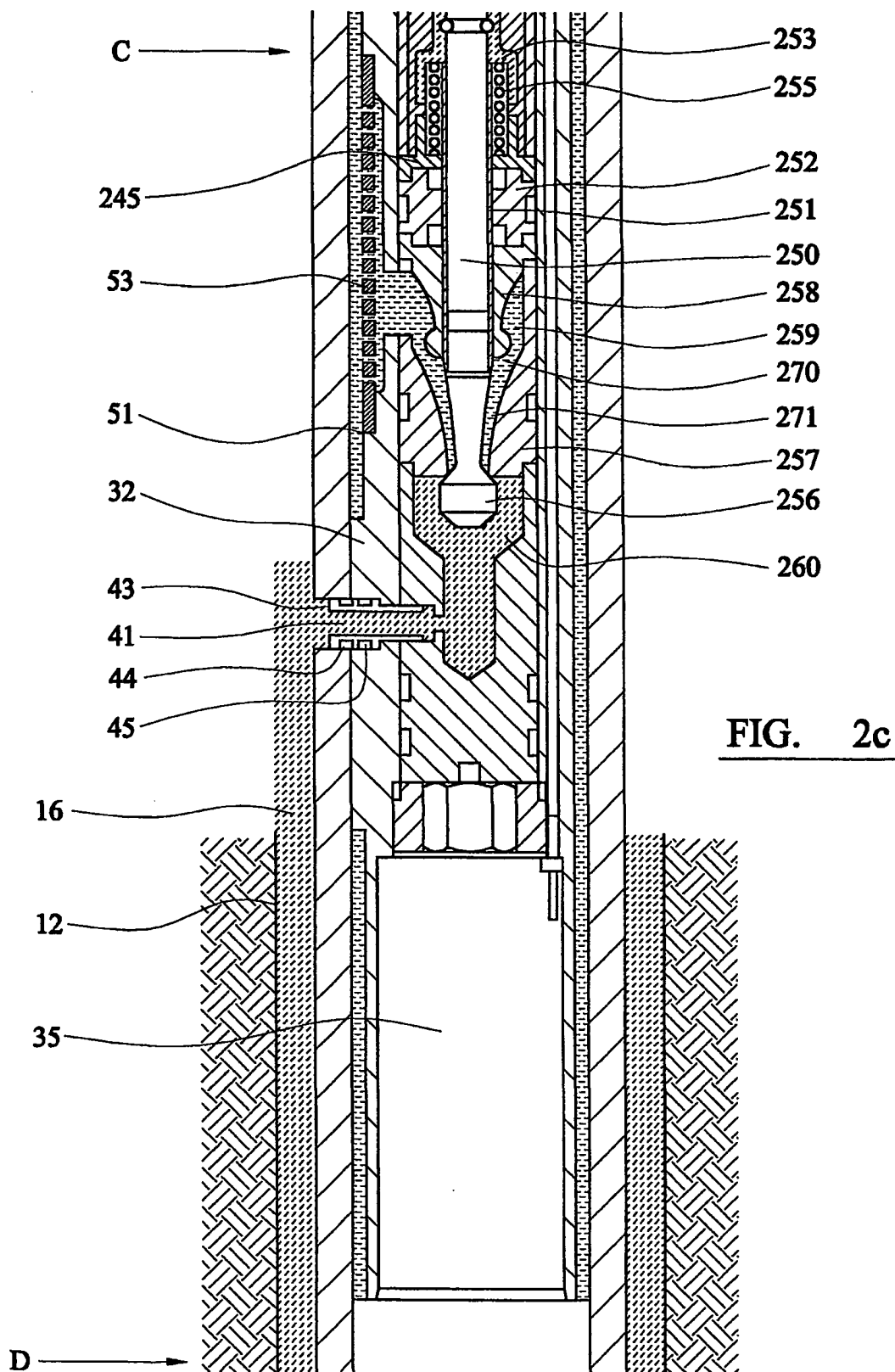


FIG. 2b

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-5/9-

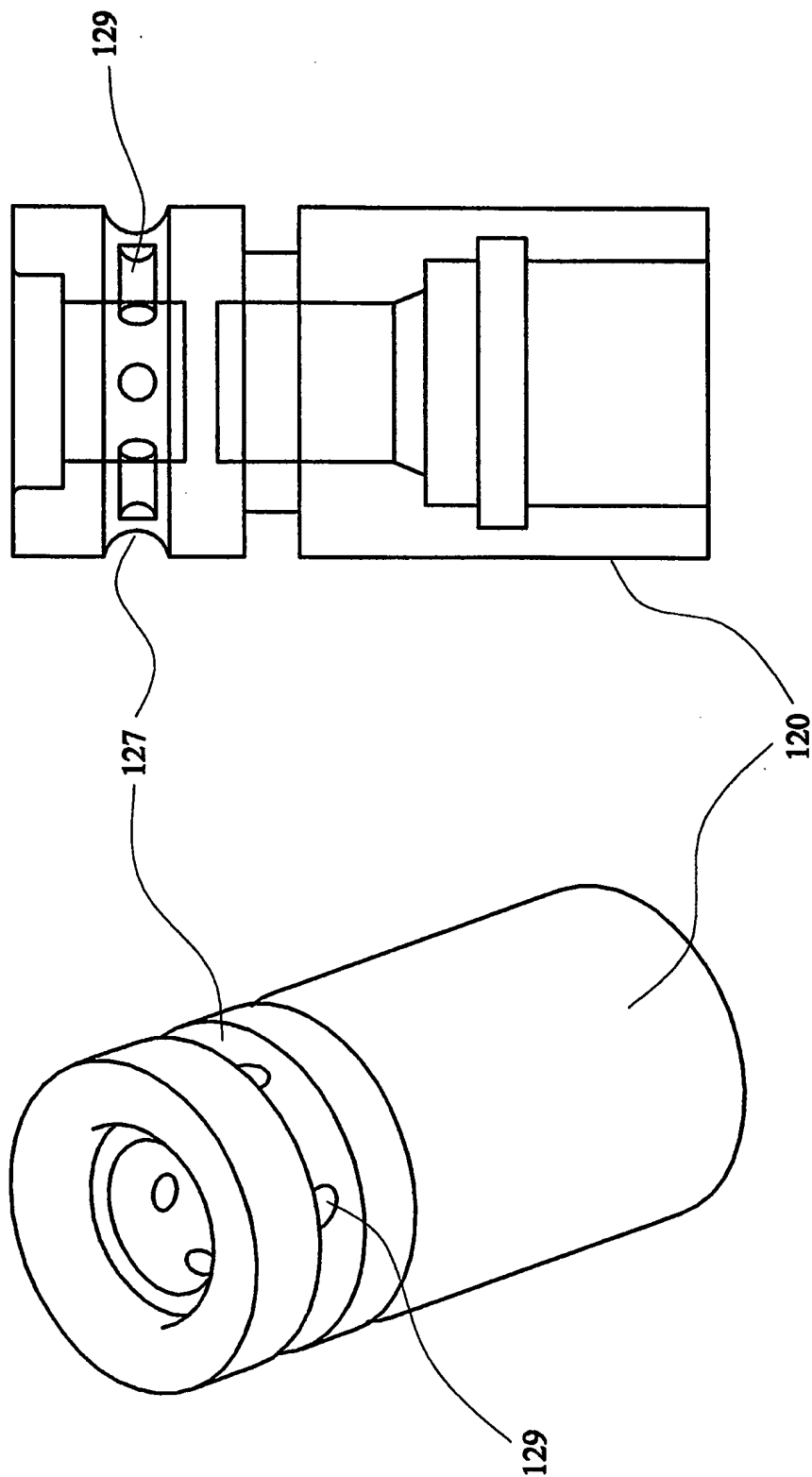


FIG. 3b

FIG. 3a

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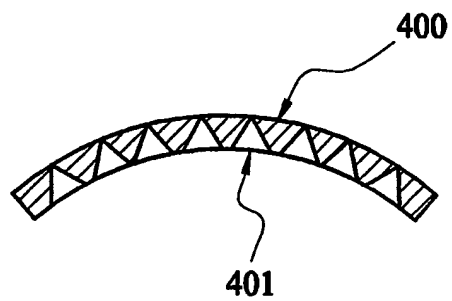


FIG. 4a

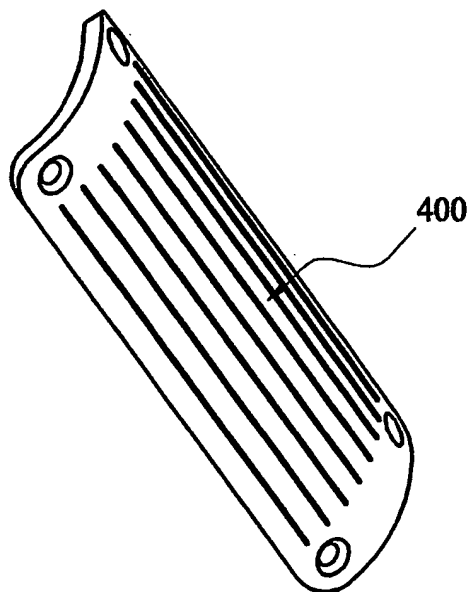


FIG. 4b

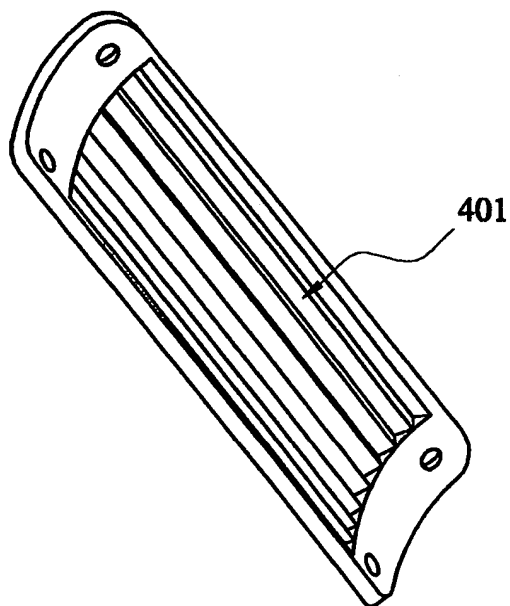


FIG. 4c

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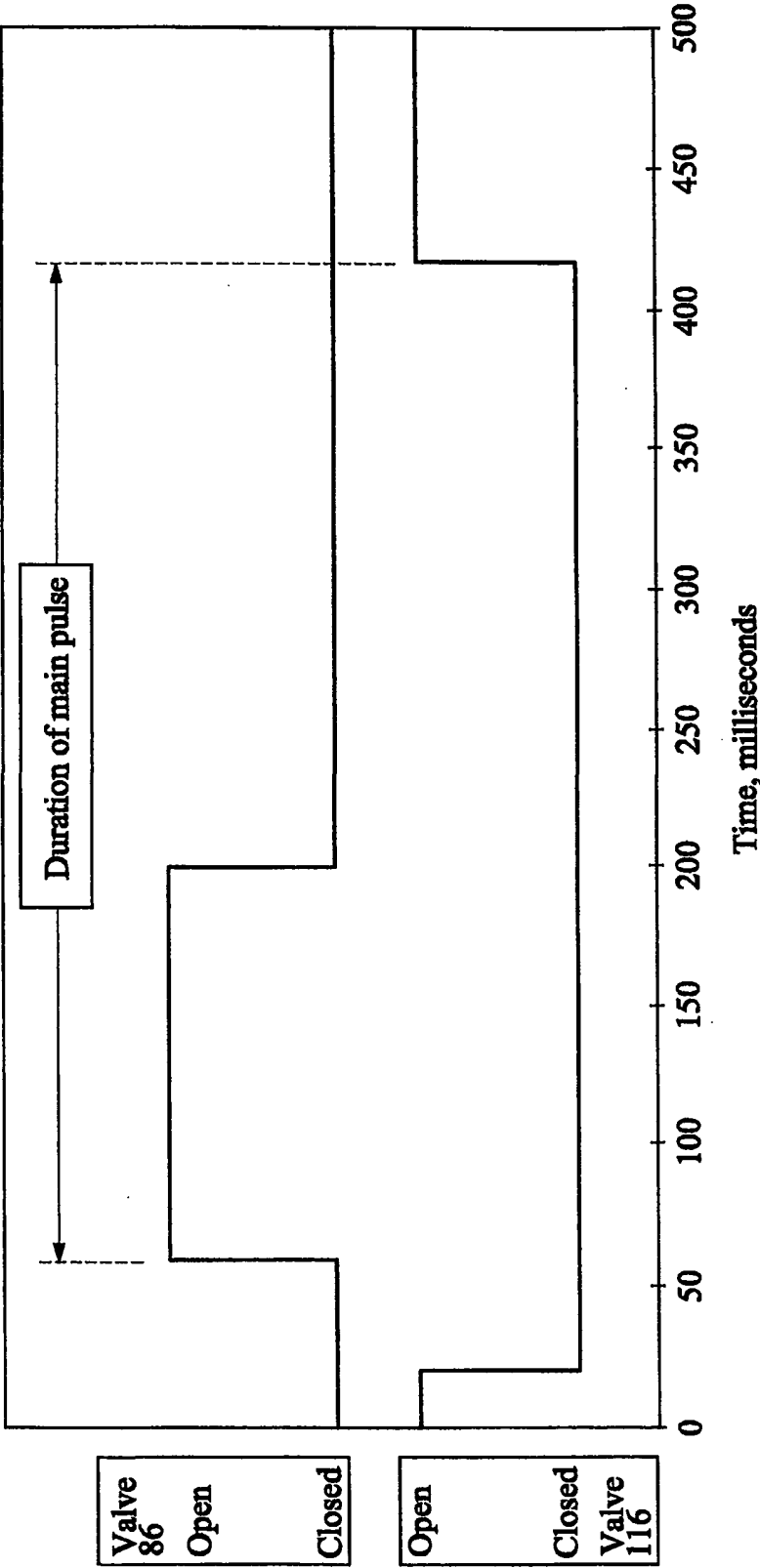


FIG. 5

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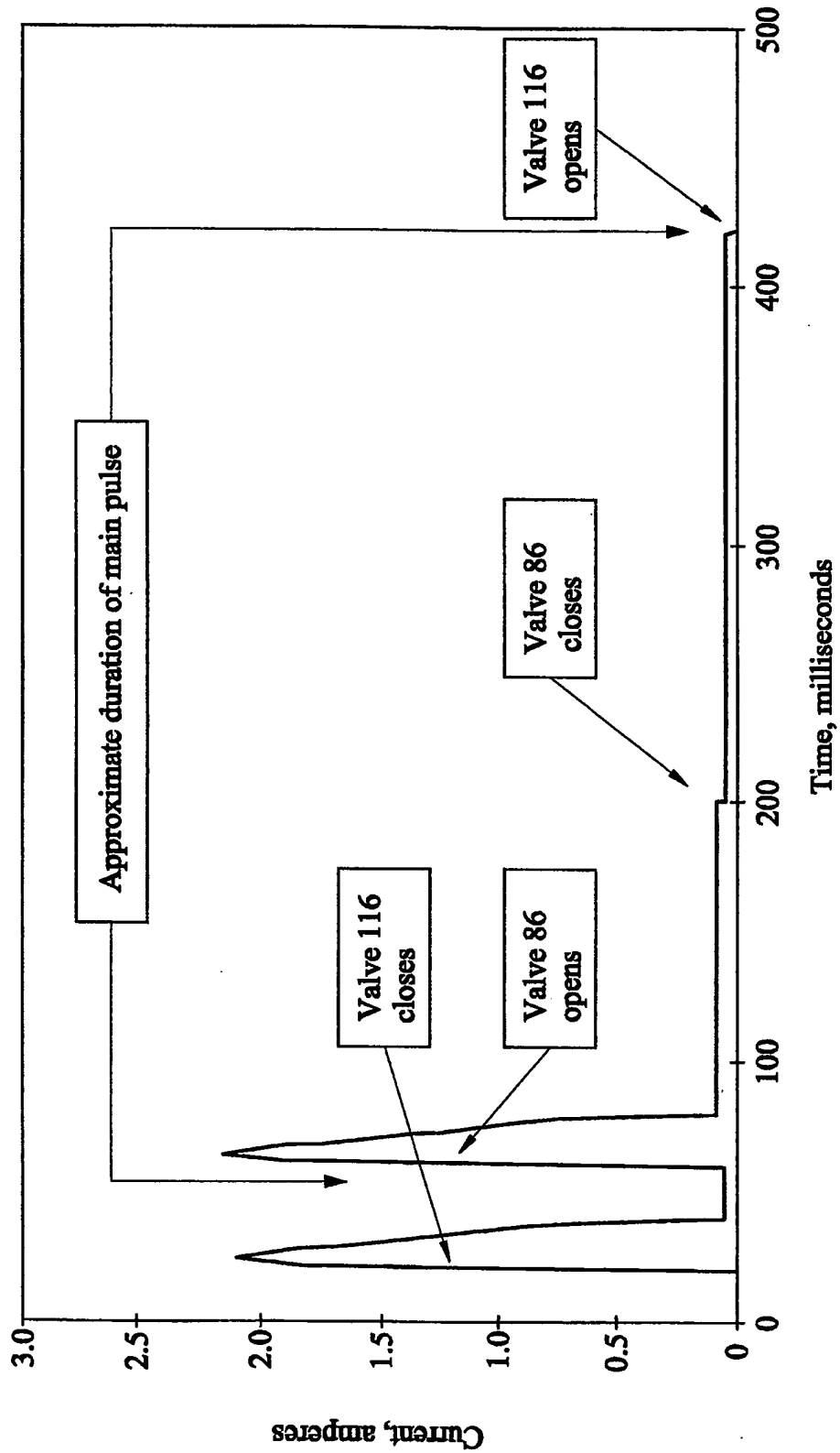


FIG. 6

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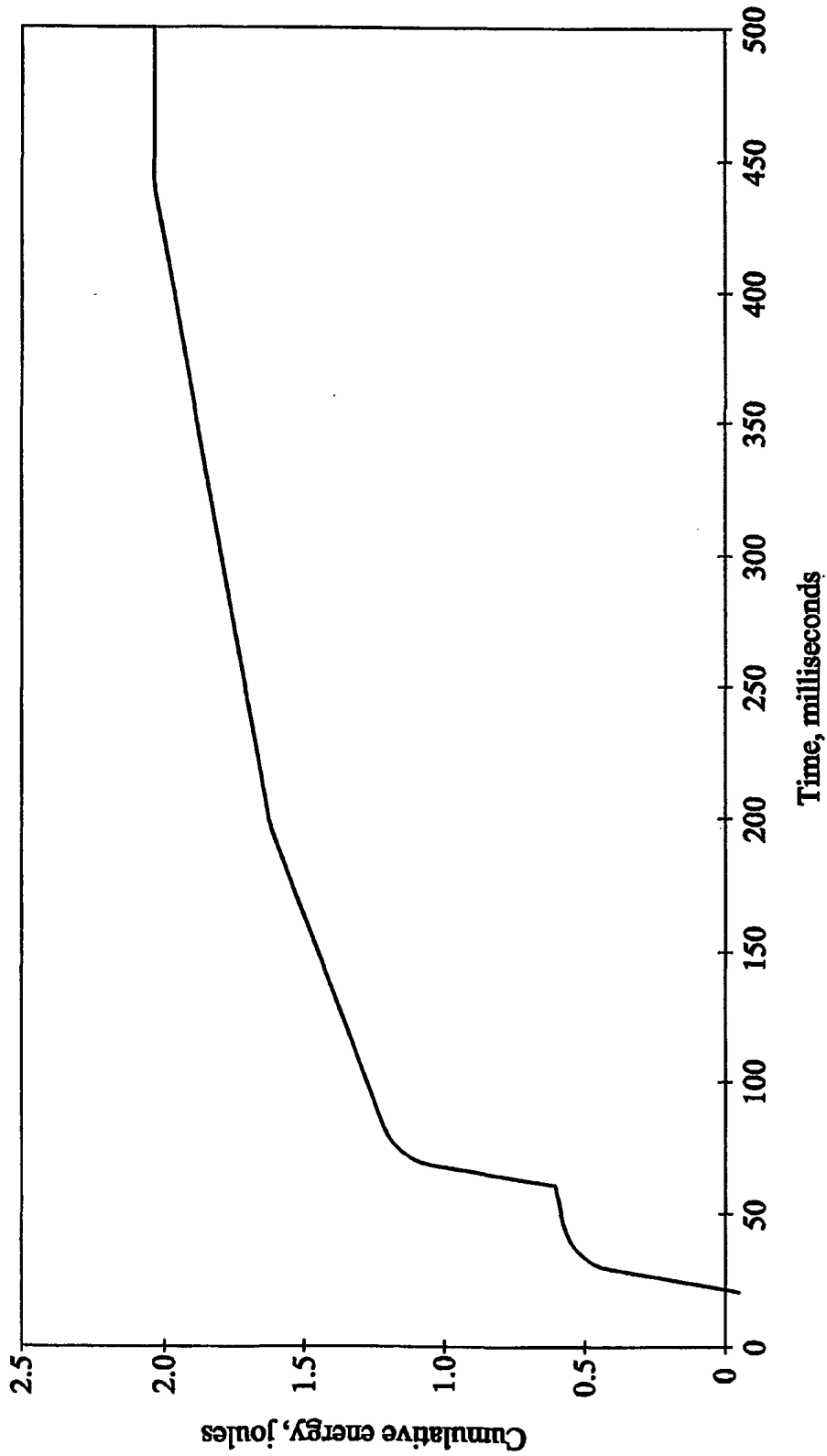


FIG. 7

INTERNATIONAL SEARCH REPORT

Inter nal Application No

PCT/GB 02/00302

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 E21B47/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 4 790 393 A (LARRONDE MICHAEL L ET AL) 13 December 1988 (1988-12-13) column 3, line 39 - line 53; figure 2	1,2,4
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A	US 4 742 498 A (BARRON C DWAIN) 3 May 1988 (1988-05-03) claim 1	1,4



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Patent family members are listed in annex.

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Date of the actual completion of the international search

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International Application No

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